

Power-Efficient Infrared Security System

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Abstract — This paper presents the design and implementation of the Power-efficient infrared security system for indoor environments that offers an innovative approach to indoor security using photonic technology. Key components include an optical detection system that uses an LED-photodiode pair operating in the near-infrared spectrum 850nm to detect human presence, coupled with signal processing using modulation of LED and fast fourier transform to extract the signal, a battery-backed power management system, a camera module for visual verification, and alarm functionality integrated through a user-friendly mobile application. The PIESS achieves 80% detection accuracy with a range of 1 meter and a response time less than 10 seconds. This paper examines the hardware design considerations, software architecture, and performance evaluation of this innovative security solution.

I. INTRODUCTION

Indoor security represents a persistent challenge in both residential and commercial settings, requiring solutions that balance effective monitoring with practical constraints including power consumption, reliability, and user experience. Traditional security systems often rely on continuous video surveillance or passive infrared (PIR) motion detection, approaches that present significant drawbacks including high power consumption, limited detection accuracy, and frequent false alarms [1].

The Power-efficient Infrared Security System (PEISS) addresses these limitations by implementing an innovative LED-photodiode detection approach operating in the near-infrared spectrum. By analyzing reflected infrared light patterns, the system can effectively detect human presence while consuming significantly less power than camera-based alternatives in indoor security technology, offering several key innovations:

- 1) Energy-efficient optical sensing using LED-photodiode technology that requires minimal

power while maintaining reliable detection capabilities

- 2) Signal modulation and Fast Fourier Transform processing to distinguish object presence from ambient interference
- 3) Hybrid power system incorporating both AC mains and battery backup to ensure continuous operation
- 4) Wireless connectivity and mobile application interface for convenient monitoring and control
- 5) Automatic image capture upon detection for visual verification of security events

II. HARDWARE DESIGN

A. Optical System

The PEISS optical system operates on a reflection-based detection principle. Two SFH 4550 LEDs emit 850nm infrared radiation modulated at 10kHz with a 50% duty cycle. When an object enters the detection zone, a portion of this radiation reflects back to the SFH 203 photodiode. The returning signal maintains the 10kHz signature, which is then isolated from ambient noise using frequency domain analysis.

The decision to employ the SFH 4550 LED represents a significant optimization from the initially considered TSHG6400. While the TSHG6400 offered a wider beam angle ($\pm 27^\circ$), the SFH 4550 provided substantially higher radiant intensity (700mW/sr vs. 70mW/sr), enabling detection at greater distances despite its narrower beam. This high-intensity, narrow-beam approach proved more effective for the motion detection application than a wider, lower-intensity alternative.

To further improve detection distance we opted to add a second IR LED and operate them simultaneously to add signal strength while remaining within safety limits. Each SFH 4550 LED driven at 100mA (using a 33 Ω resistor with a 5V supply) produces a radiant intensity of 700mW/sr.

$$I = 2 * 700 \text{ mW/sr} = 1400 \text{ mW/sr} \quad (1)$$

The power of the LEDs is:

$$P = I * A \quad (2)$$

Accounting for solid angle:

$$\Omega = 2\pi(1 - \cos(\frac{\theta}{2})) = 0.0087 \text{ sr} \quad (3)$$

The resulting power emitted is:

$$P = 1400 * 0.0087 = 12.06 \text{ mW} \quad (4)$$

The beam expands as it moves away from the source, forming a circle with radius at a distance of 100 cm

The beam radius is given by:

$$Rb = r \times \tan\left(\frac{\theta}{2}\right) = 100 \times \tan\left(\frac{3}{2}\right) = 5.24 \text{ cm} \quad (5)$$

The cross sectional area is:

$$A = \pi \times Rb^2 = 86.29 \text{ cm}^2 \quad (6)$$

Then Irradiance is:

$$E = \frac{P}{A} = \frac{12.06}{86.29} = 0.14 \text{ mW/cm}^2 \quad (7)$$

Which is within the safety limits for short term (100 mW/cm^2) and long term (10 mW/cm^2) exposure.

When infrared radiation encounters a human subject, the reflection coefficient varies significantly depending on clothing, skin tone, and incidence angle. Our testing revealed substantial variations in performance based on clothing color. For practical calculations, we use reflection coefficients of:

- 1) 10% for light-colored clothing
- 2) 5% for normal/medium-colored clothing
- 3) 2% for dark clothing

For normal clothing (5% reflectance):

$$E(r) = 0.14 \text{ mW/cm}^2 \times 0.05 = 0.007 \text{ mW/cm}^2 \quad (8)$$

For dark clothing (2% reflectance):

$$E(r) = 0.14 \text{ mW/cm}^2 \times 0.02 = 0.0028 \text{ mW/cm}^2 \quad (9)$$

The reflected radiation follows an approximately Lambertian distribution (cosine law), spreading in multiple directions. The portion returning to the photodiode decreases according to the inverse square law:

$$E(\text{received}) = \frac{E(r) \times A(\text{receptor})}{4\pi \times r^2} \quad (10)$$

Where $A(\text{receptor})$ is the active area of the photodiode ($1 \text{ mm}^2 = 0.01 \text{ cm}^2$). At 1 meter for normal clothing:

$$E(\text{received}) = \frac{0.007 \text{ mW/cm}^2 \times 0.01 \text{ cm}^2}{(4\pi \times (1\text{m})^2)} = 5.57 \text{ nW} \quad (11)$$

For dark clothing:

$$E(\text{received}) = \frac{0.0028 \text{ mW/cm}^2 \times 0.01 \text{ cm}^2}{(4\pi \times (1\text{m})^2)} = 2.23 \text{ nW} \quad (12)$$

The Green.L 850nm filter with >90% transmission at 850nm modifies the received power for normal clothing:

$$E(\text{filtered}) = 5.57 \text{ nW} \times 0.90 = 5.01 \text{ nW} \quad (13)$$

And for dark clothing:

$$E(\text{filtered}) = 2.23 \text{ nW} \times 0.90 = 2.01 \text{ nW} \quad (14)$$

With the SFH 203 photodiode responsivity of 0.62 A/W at 850nm, the generated photocurrent for normal clothing is:

$$I_p = 5.01 \text{ nW} \times 0.62 \text{ A/W} = 3.11 \text{ nA} \quad (15)$$

And for dark clothing:

$$I_p = 2.01 \text{ nW} \times 0.62 \text{ A/W} = 1.24 \text{ nA} \quad (16)$$

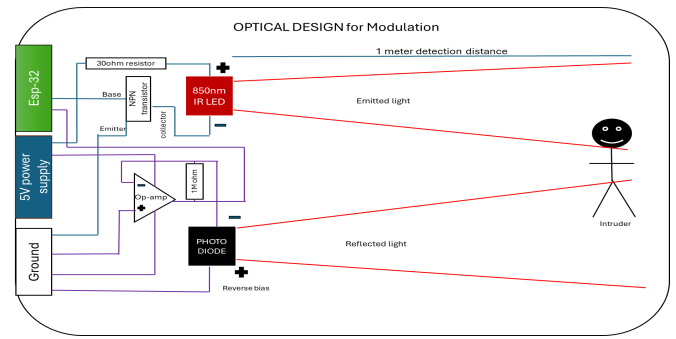


Fig. 1. Optical Design

The modulated signal is generated by the ESP32 using pulse-width modulation (PWM) capabilities, which produces a reliable 10kHz square wave. To effectively modulate the high-power SFH 4550 LED, an NPN transistor (2N2222) is employed as a switching element between the ESP32 and the LED. This configuration allows the low-current GPIO output from the ESP32 to control the higher current required by the LED (approximately 100mA), while enabling rapid switching at the 10kHz modulation frequency.

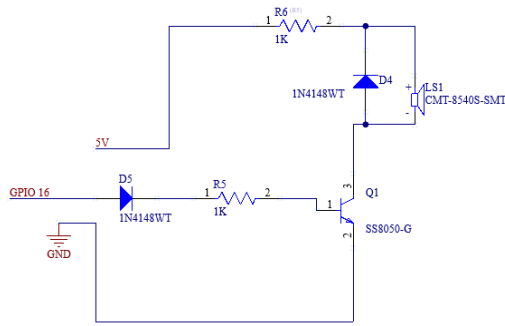


Fig. 4. Schematic for Alarm Circuit

C. Camera System

The camera system serves a vital function of the PEISS and other home security systems: the ability to capture an image of an incident. The image capturing system of the project implements a CMOS camera module over other camera modules. The CMOS module offered advantages over competitors in price and power consumption while not sacrificing image quality. This section will highlight the component selection and design parameters.

The Arducam Mini 2MP Plus - OV2640 was selected with power consumption in mind. It also features a compact size, with the ability to capture 2-megapixel images. The OV2640 CMOS sensor utilizes JPEG compression, which helps reduce the processing load on the ESP32 and still allows for efficient storage and transmission of images. The module is interfaced with SPI, allowing for seamless connection to the ESP32, while ensuring dependable data transfer and minimal latency for image capturing. Additionally, the SPI interface allows for adjustable image brightness, contrast, saturation, and many other image editing settings, a key addition as it allows us to configure the module to work in various lighting environments.

The OV2640 module will be connected to the main PCB using jumper wires and an eight pin female header, illustrated in Fig. 5.

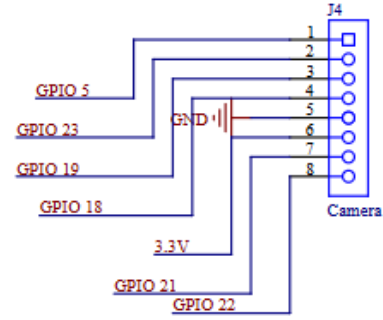


Fig. 5. Schematic for Camera connection to the ESP32

D. Microcontroller

The core of the PEISS will be the ESP32-WROOM-32E microcontroller. The ESP32 meets key requirements of our project and oftentimes excels at them. With the design of this project being aimed towards low power consumption while providing the ability to communicate wirelessly in real-time, the decision to implement the ESP32 was made.

The chip provides the ability to utilize several different low power modes to optimize the consumption of a system and excels in real-time applications involving sensors. With the chip running in the range of 80-240 MHz, it will provide more than enough processing power to handle the tasks required by the PEISS. The chip also meets the memory requirements for the system as it has 520 KB of SRAM and 4 MB of flash memory. The microcontroller will be developed using the Arduino IDE.

E. Power System

The Power System Unit (PSU) is designed to ensure uninterrupted operation, efficient power conversion, and seamless switching between primary and backup power sources. The system operates on 120VAC main power, which is converted to 5VDC, while a battery backup provides power during outages. A relay-based priority switching system ensures automatic switchover between power sources, and a switching voltage regulator steps down the system voltage from 5V to 3.3V for powering the ESP32 microcontroller and other components.

The primary power source for the system is 120VAC, which is converted to 5VDC using an IMR-15-5 AC-DC converter. This converter was selected for its compact size, 3A output current, and high efficiency (78%), ensuring a reliable power supply with sufficient headroom for both the system load and battery charging.

A 0.5A fuse is used on the AC input line to protect against overcurrent conditions.

A backup power source was integrated to maintain operation during power outages. The DFRobot 4-slot 18650 battery holder was chosen due to its built-in charging module, battery management system (BMS), and overcharge/over-discharge protection. The battery pack provides a regulated 5V output at 2A, ensuring sufficient power to keep the system running when AC power is unavailable.

A relay-based priority switching system was implemented to ensure automatic switching between main power and backup power. A J104B2C5VDC.20S DPDT mechanical relay was selected due to its ability to handle both power legs simultaneously, open-before-close switching, and low power consumption for its coil. The switch between the two legs takes approximately 20 msec. To ensure power isn't lost to the system during this switch, large capacitors will be implemented between the relay output and ground.

The system requires a 3.3V power rail for the ESP32 microcontroller and other components. To efficiently step down the 5VDC supply, a LM2596S adjustable switching voltage regulator was chosen. This regulator was selected for its lower switching frequency of 150 kHz and efficiency rating of (~75%-80%). The board layout for this regulator will be shown in Fig. 6.

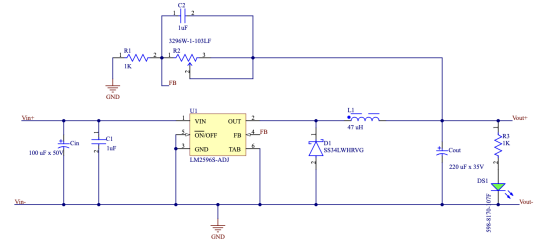


Fig. 6. Schematic for the LM2596 regulator

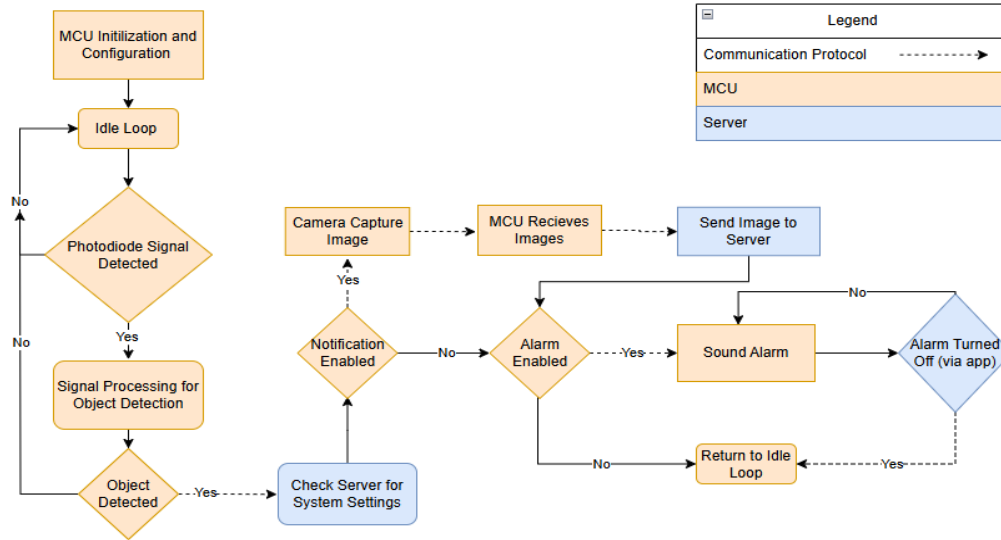


Fig. 7. Microcontroller Software Control Flow

III. SOFTWARE DESIGN

The software design of this project was planned and implemented to provide a user-friendly and reliable interface for monitoring and controlling the security system. This section outlines the design principles and structural components that define how the software operates and interfaces with the hardware components.

A. Microcontroller Programming

Key functionalities for the PEISS include processing photodiode signals to detect object presence, managing communication with a remote server, controlling system hardware (such as alarm, camera, and LED modulation), and responding to user commands through a mobile app.

These operations are orchestrated by an ESP32 microcontroller, chosen for its versatility, processing

power, and energy efficiency. This section provides an in-depth overview of the ESP32's software control flow, detailing the specific software functions that enable these features and ensure seamless interaction across the system's components.

As depicted in Figure 7, the project begins with the initialization and configuration. This stage includes setting up communication protocols, such as Wi-Fi, configuring GPIO pins, and initializing any necessary peripherals like the LED, camera module, and alarm. During the configuration stage, we also calibrated the photodiode to determine its baseline reading when no object is present. This baseline serves as a threshold to detect significant changes indicating object detection.

Once initialization is complete, the program enters the main loop, which continuously monitors the photodiode signal. In this loop, 256 samples are taken from GPIO pin 36 (ADC0), and a Fast Fourier Transform (FFT) is performed on the collected data. The program then examines the frequency domain, specifically at the modulation frequency of the LED. If the amplitude at this frequency exceeds the threshold, the system enters the object detection phase.

Here the microcontroller continues to sample and perform FFT; if it detects three consecutive readings above the threshold, an object is confirmed.

Upon confirmation, the MCU communicates with the server over Wi-Fi using HTTP protocols to retrieve system settings configured by the user via the mobile app. These settings determine whether the alarm should be activated and if notifications should be sent.

Based on these settings, the MCU either triggers the alarm and or sends a captured image to the server. If the alarm is disabled or manually turned off via the app, the microcontroller returns to the main loop, awaiting the next detection event.

B. Backend

Our project's backend is a robust system that integrates a DigitalOcean server, a MongoDB database, and a series of APIs built with Node.js and Express.js.

Initially, the DigitalOcean server was set up and configured to serve as the central hub, managing incoming requests and facilitating secure, efficient communication between the user, microcontroller, and database.

Once the server was operational, a MongoDB cluster was created to host our data, and several collections were set up within this cluster. These collections serve as containers for different types of data allowing us to organize and manage data efficiently. Collections specifically were designed for user information, system settings, and detection logs.

With the data infrastructure in place, we developed the API endpoints. Each API endpoint was meticulously created and rigorously tested to ensure proper functionality before any frontend development began. Testing was all done through Swaggerhub, which involved verifying that every endpoint returns a 200 status response upon successful API calls, and that improper JSON in the request body produces appropriate error messages. The APIs were comprehensively documented and deployed to the server by uploading the code to a Github repository and using the Windows terminal to pull the changes directly onto the server.

C. Frontend

On the frontend, extensive planning and design of the user interface were conducted prior to coding to ensure a user-friendly experience. A consistent dark theme was maintained across all screens to ensure a unified aesthetic. The companion app was developed using Flutter, which allows a single codebase to run on both Apple and Android devices, ensuring that the app's look and functionality remain consistent across platforms.

The app comprises six distinct screens:

- 1) Sign-in Screen: Allows users to securely log in.
- 2) Register Screen: Enables new users to create an account.
- 3) Disconnected Screen: Informs the user that they must connect to the system and offers an option to establish connection.
- 4) Connected Screen: Displays when the user is connected to the system and provides controls for toggling the alarm and managing notifications.
- 5) Activity Logs Screen: Allows users to view all detection events along with timestamps.
- 6) Detailed Event Screen: Provides an in-depth view of individual events

Front-end testing was conducted using an Android Studio emulator during the development. Moreover, the app leverages Firebase for Android notifications along with Apple Push Notifications for iOS, ensuring that users receive timely alerts regardless of their device.

IV. HOUSING

A. Optical Housing

The optical system requires precise positioning of the LEDs and photodiode components to ensure optimal detection performance. A custom optical housing was designed to maintain consistent alignment between these components while providing protection from environmental factors and physical damage.

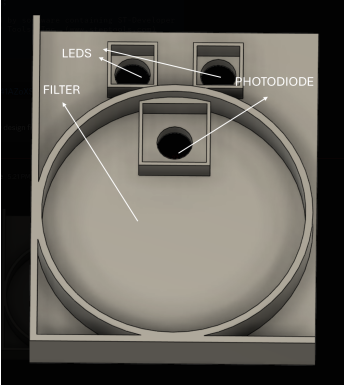


Fig. 8. Structural illustration of the optical housing showing component placement.

B. Main Housing

The main housing of the system is designed to securely enclose all components while ensuring safe operation and ease of maintenance. It is divided into four primary sections: the battery compartment, the main PCB area, the power conversion area, and the lid. Each section was designed using Autodesk Fusion 360 and 3D printed in the lab to ensure a compact, well-structured, and functional enclosure.

The main PCB area serves as the central hub of the system, housing both the main PCB board and the voltage regulator board. This area incorporates the wire routing between the power converter, battery holder, and main PCB, ensuring an organized layout for power and data connections. Holes were also added in the design to ensure dissipation of heat, USB accessibility, and allowing the alarm sound to escape the housing. The placement of the PCB within this section provides easy access for debugging and maintenance, while keeping the system compact and efficient.

The battery compartment is positioned at the bottom of the main housing, allowing for easy and safe battery replacement. This placement reduces the risk of accidental exposure to high-voltage components, as users only need to access the lower section when replacing batteries. A dedicated wiring channel connects the battery compartment to the main PCB and power conversion areas, ensuring a secure and organized power distribution pathway.

The power conversion area is physically separated from the main PCB area by a safety barrier to prevent accidental contact with high-voltage components. This section houses; the 120VAC to 5VDC converter, a 0.5A fuse for circuit protection, and the primary AC power leads. To enhance safety, this section is secured with a screw-down lid, preventing unauthorized access while still

allowing maintenance when necessary. The separation of the low-voltage and high-voltage sections minimizes electrical hazards and improves overall system safety.

The lid assembly houses the system's optical components, including the camera module, the infrared LED (IR LED) board, the photodiode sensor board, and the optical housing. The lid is designed as a removable, screw-down panel, ensuring secure attachment to the main housing while still allowing easy access for system maintenance, sensor adjustments, or component replacements. The placement of the optical components in the lid ensures optimal positioning for surveillance and detection while maintaining a compact and well-protected design.

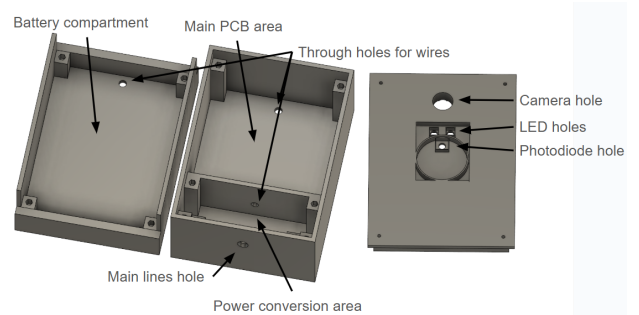


Fig. 9. Structural illustration of the main house

V. ENGINEERING SPECIFICATIONS TESTING

This section presents the engineering specifications for the PEISS, encompassing hardware, software, and overall operational parameters.

TABLE I. ENGINEERING SPECIFICATIONS

Accuracy	At least 80%
Detection Distance	At least 2.5ft
Response Time	< 10 seconds
Power Consumption	< 2 W
Mobile Compatibility	iOS and Android
Backup Power	Rechargeable Battery
Alert	Alarm and Push Notifications

As seen in Table 1, the system's primary operational parameters include accuracy, maximum detection distance, and response time. These parameters are fundamental to the system's functionality, and therefore, both hardware and software components were rigorously tested and refined to optimize performance.

The testing criteria assume a scenario in which an individual wearing light-colored clothing walks at a normal pace in front of the security system. Consequently all evaluations were conducted under these conditions to ensure consistency and reliability in real-world applications.

A. Detection Distance

The maximum detection range of our system is specified to be at least 2.5 feet (0.77 meters). Initially, the system achieved a maximum range of only 30 cm, which was insufficient for a security application. This limitation was addressed by modulating the LED and applying FFT to the signal processing.

With these changes to the signal processing, the maximum range improved to 70 cm. Although this was an improvement, it still fell short of our target. Therefore, we made a trade-off by increasing power-consumption and adding a second LED to the system. The additional LED emitted more light, resulting in greater reflection from objects placed in front of the system, which further extended the detection range to 3 feet. This trade-off in power consumption was considered worthwhile given the significant improvement in detection range.

Testing of the final optical system and signal processing was conducted over 20 trials at various distances:

TABLE II. DISTANCE TESTING RESULTS

Distance	Accuracy
≤ 0.305 m (1 ft.)	20/20 (100 %)
≤ 0.610 m (2 ft.)	20/20 (100 %)
≤ 0.914 m (3 ft.)	18/20 (90%)
≥ 1 m (~3.3 ft.)	5/20 (25%)

As shown in Table 2, the system will consistently detect objects with nearly 100% accuracy at distances below 3 feet. At around 3 feet, the detection rate drops slightly to around 90%, and at 1 meter (3.3 feet), the accuracy decreases substantially, lower than the target accuracy.

Therefore, we define the maximum detection distance of the system to be approximately 3 feet (.95 meters).

B. Response Time

The system's response time is measured from the moment a person enters the detection range of the security system until a notification appears on their phone. During distance testing, the average time required for signal processing and alarm activation was approximately 1.3 seconds. In addition, the user receives a push notification on average 2.5 seconds after detections.

Therefore, the system's overall average response time, encompassing both detection and notification, is approximately 4 seconds.

C. Accuracy

Accuracy detection was conducted in a controlled environment and monitored over a continuous 45-minute period. Additionally, a controlled detection event was initiated at 5 minute intervals to assess the number of missed detections.

The results from this test were as followed:

- 1) False Alarms: 1
- 2) Correct Detections: 8
- 3) Missed Detections: 1

Thus, the accuracy of the system:

$$Acc. = \frac{Correct\ Detections}{False\ Alarms + Correct. + Missed} = 80\% \quad (17)$$

VI. RESULTS

The hardware is designed for low power consumption (at most 2 Watts) and includes a backup power source for the primary AC supply. Additionally, a mobile application delivers push notifications to alert users of detections and is compatible with both iOS and Android platforms.

Regarding the test results of the primary engineering specifications, the system achieves an accuracy of at least 80% under specific conditions (e.g. within a 45-minute test period, though further clarification of this condition is recommended). While the detection distance can reach up to 100 meters (3.3 feet), the accuracy decreases at this point. Our tests indicate that the maximum detection distance with sufficient accuracy is approximately 3 feet. Moreover, the average overall response time of the system is 4 seconds, which is significantly less than the required 10 seconds. This allows for additional time to accommodate delays due to user internet connectivity issues.

Overall, the system meets the necessary performance constraints as well as its software and hardware requirements.

VII. CONCLUSION

The Power-efficient Infrared Security System (PEISS) successfully demonstrates the viability of LED-photodiode

technology for energy-efficient human detection in indoor security applications. By combining carefully selected optical components with intelligent signal processing and power management, the system achieves reliable detection performance while consuming significantly less power than camera-based alternatives.

These achievements demonstrate the potential for advanced optical sensing technologies to enhance security system performance while reducing energy requirements.

The PEISS represents a practical solution for residential and small commercial security applications where reliability, ease of use, and energy efficiency are primary concerns.

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REFERENCES

- [1] H. Chow, "Home security system," ECE 4760 Final Projects, Cornell University, 2004. [Online]. Available: <https://people.ece.cornell.edu/land/courses/ece4760/FinalProjects/s2004/ch236/securitysystem.pdf>
- [2] "MSP430G2x53 MSP430G2x13 MIXED SIGNAL MICROCONTROLLER FEATURES; For Complete Module Descriptions, See the MSP430x2xx Family User's Guide (SLAU144)," 2011. Available: <https://www.ti.com/lit/ds/symlink/msp430g2553.pdf>